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Extra Matter at Low Energy*

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Abstract

Assuming that the Standard Model arises from the $E_8 \times E_8$ Heterotic Superstring, we try to solve the discrepancy between the unification scale predicted by this theory ($\approx g_{GUT} \times 5.27 \cdot 10^{17}$ GeV) and the value deduced from LEP experiments ($\approx 2 \cdot 10^{16}$ GeV). This will allow us to predict the presence at low energies of three generations of supersymmetric Higgses and vector-like colour triplets.

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1 Introduction

Although the Standard Model of particle physics provides a correct description of the observable world, there exist strong indications that it is just a low-energy effective theory. There is no answer in the context of the Standard Model to some fundamental questions. For example, how can we unify it with gravity? And then: How can we protect the masses of the scalar particles against quadratic divergences in perturbation theory (the so-called hierarchy problem)? Other questions cannot even be posed: Why is the Standard Model gauge group $SU(3) \times SU(2) \times U(1)_Y$? Why are there three families of particles? Why is the pattern of quark and lepton masses so weird?

In fact, only Superstring Theory has the potential to unify all gauge interactions with gravity in a consistent way being able to answer all the above questions. In this sense, it is a crucial step to build a consistent Superstring Theory in four dimensions accommodating the observed Standard Model, i.e. we need to find the SuperString Standard Model (SSSM).

In the late eighties, the compactification of the $E_8 \times E_8$ Heterotic String on six-dimensional orbifolds proved to be an interesting method to carry out this task (for a brief historical account see the Introduction in ref. [1] and references therein). It was shown that the use of two Wilson lines on the torus defining the symmetric Z_3 orbifold can give rise to four-dimensional supersymmetric models with gauge group $SU(3) \times SU(2) \times U(1)^5 \times G_{hidden}$ and three generations of chiral particles. In addition, it was also shown that the Fayet–Iliopoulos D-term, which appears because of the presence of an anomalous $U(1)$, can give rise to the breaking of the extra $U(1)$'s. In this way it was possible to construct [2, 3, 4] supersymmetric models with gauge group $SU(3) \times SU(2) \times U(1)_Y$, three generations of particles in the observable sector, and absence of dangerous baryon- and lepton-number-violating operators¹.

Unfortunately, we cannot claim that one of these models is the SSSM, since several problems are always present. Let us concentrate on two of them. First of all, although the initially large number of extra particles, which are generically present in these constructions, is highly reduced through the Fayet–Iliopoulos mechanism, since many of them get a high mass ($\approx 10^{16-17}$ GeV), some extra $SU(3)$ triplets, $SU(2)$ doublets and $SU(3) \times SU(2)$ singlets still remain. On the other hand, given the predicted value for the unification scale in the Heterotic String [6], $M_{GUT} \approx g_{GUT} \times 5.27 \cdot 10^{17}$ GeV, the values of the gauge couplings deduced from LEP experiments cannot be obtained [7]. Recall that this is only possible in the context of the minimal supersymmetric standard model (MSSM) for $M_{GUT} \approx 3 \times 10^{16}$ GeV.

¹Recently another model has been partially analyzed [5].

In any case, it is plausible to think that another orbifold model could be found with the right properties. In the present talk we will adopt this point of view, and we will try to deduce the phenomenological properties that such a model must have in order to solve the two important problems mentioned above. In fact, both problems, extra matter and gauge coupling unification, are closely related, since the evolution of the gauge couplings from high to low energy through the RGEs depends on the existing matter. With our solution we will be able to predict the existence of three generations of supersymmetric Higgses and vector-like colour triplets at low energies [1].

2 Predictions from the unification of α_3 with α_2

Since we are interested in the analysis of gauge couplings, we need to first clarify which is the relevant scale for the running between the supersymmetric scale M_S and the unification point. Let us recall that in heterotic compactifications some scalar singlets χ_i develop VEVs in order to cancel the Fayet–Iliopoulos D-term, without breaking the Standard Model gauge group. An estimate about their VEVs can be done with the average result $\langle \chi_j \rangle \sim 10^{16-17}$ GeV. After the breaking, many particles, say ξ , acquire a high mass because of the generation of effective mass terms. These come for example from operators of the type $\chi_i \xi \xi$. In this way extra vector-like triplets and doublets and also singlets become very heavy. We will use the above value as our relevant scale, the so-called Fayet–Iliopoulos scale $M_{FI} \approx 10^{16-17}$ GeV.

As discussed in the Introduction, we are interested in the unification of the gauge couplings at $M_{GUT} \approx g_{GUT} \times 5.27 \cdot 10^{17}$ GeV. Let us try to obtain this value by using first the existence of extra matter at the scale M_S . We will see that this is not sufficient and the Fayet–Iliopoulos scale must be included. Let us concentrate for the moment on α_3 and α_2 . Recalling that three generations appear automatically for all the matter in Z_3 orbifold scenarios with two Wilson lines, the most natural possibility is to assume the presence of three light generations of supersymmetric Higgses. This implies that we have four extra Higgs doublets, $n_2 = 4$, with respect to the case of the MSSM. Unfortunately, this goes wrong. Whereas α_3^{-1} remains unchanged, since the number of extra triplets $n_3 = 0$, the line for α_2^{-1} is pushed down with respect to the case of the MSSM. As a consequence, the two couplings cross at a very low scale ($\approx 10^{12}$ GeV). We could try to improve this situation by assuming the presence of extra triplets in addition to the four extra doublets. Then the line for α_3^{-1} is also pushed down and therefore the crossing might be obtained for larger scales. However, even for the minimum number of extra triplets that can be naturally obtained in our scenario, $3 \times \{(3, 1) + (\bar{3}, 1)\}$,

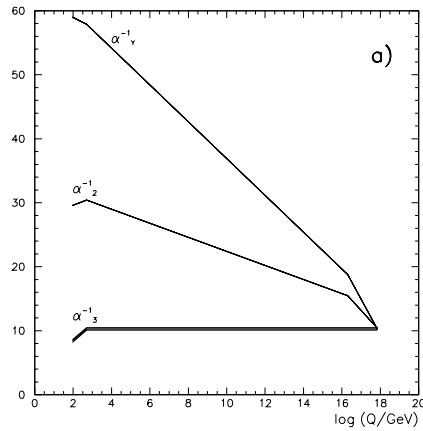


Figure 1: Unification of the gauge couplings at $M_{GUT} \approx g_{GUT} \times 5.27 \cdot 10^{17}$ GeV with three light generations of supersymmetric Higgses and vector-like colour triplets. In this example we show one of the four possible patterns of heavy matter in eq. (2), in particular that with $n_3^{FI} = 0$. The line corresponding to α_1 is just one of the many possible examples.

i.e. $n_3 = 6$, the “unification” scale turns out to be too large ($\approx 10^{21}$ GeV). One can check that other possibilities including more extra doublets and/or triplets do not work [1]. Thus, using extra matter at M_S we are not able to obtain the Heterotic String unification scale since α_3 never crosses α_2 at $M_{GUT} \approx g_{GUT} \times 5.27 \cdot 10^{17}$ GeV. Fortunately, this is not the end of the story. As we will show now, the Fayet–Iliopoulos scale M_{FI} is going to play an important role in the analysis.

In order to determine whether or not the Heterotic String unification scale can be obtained, we need to know the number of doublets n_2^{FI} and triplets n_3^{FI} in our construction with masses of the order of the Fayet–Iliopoulos scale M_{FI} . It is possible to show that within the Z_3 orbifold with two Wilson lines, three-generation standard-like models must fulfil the following relation for the extra matter: $2 + n_2 + n_2^{FI} = n_3 + n_3^{FI} + 12$. Then, it is now straightforward to check that only models with $n_2 = 4, n_3 = 6$, and therefore $n_2^{FI} - n_3^{FI} = 12$, may give rise to the Heterotic String unification scale [1] (the other possibilities for n_2, n_3 , mentioned above do not even produce the crossing of α_3 and α_2). This is shown in Fig. 2 for an example with $n_3^{FI} = 0$, and assuming $M_S = 500$ GeV. There we are using $M_{FI} = 2 \cdot 10^{16}$ GeV as will be discussed below.

Note that at low energy we then have (excluding singlets)

$$3 \times \{(3, 2) + 2(\bar{3}, 1) + (1, 2)\} + 3 \times \{(3, 1) + (\bar{3}, 1) + 2(1, 2)\} , \quad (1)$$

i.e. the matter content of the Supersymmetric Standard Model with three generations of Higgses and vector-like colour triplets.

Let us remark that in these constructions only the following patterns of matter with masses of the order of M_{FI} are allowed:

$$\begin{aligned}
a) \quad & n_3^{FI} = 0, \quad n_2^{FI} = 12 \quad \rightarrow \quad 3 \times \{4(1, 2)\} \quad , \\
b) \quad & n_3^{FI} = 6, \quad n_2^{FI} = 18 \quad \rightarrow \quad 3 \times \{(3, 1) + (\bar{3}, 1) + 6(1, 2)\} \quad , \\
c) \quad & n_3^{FI} = 12, \quad n_2^{FI} = 24 \quad \rightarrow \quad 3 \times \{2[(3, 1) + (\bar{3}, 1)] + 8(1, 2)\} \quad , \\
d) \quad & n_3^{FI} = 18, \quad n_2^{FI} = 30 \quad \rightarrow \quad 3 \times \{3[(3, 1) + (\bar{3}, 1)] + 10(1, 2)\} \quad . \quad (2)
\end{aligned}$$

Thus for a given Fayet-Iliopoulos scale, M_{FI} , each one of the four patterns in eq. (2) will give rise to a different value for g_{GUT} . Adjusting M_{FI} appropriately, we can always get $M_{GUT} \approx g_{GUT} \times 5.27 \cdot 10^{17}$ GeV. In particular this is so for $M_{FI} \approx 2 \times 10^{16}$ GeV as shown in Fig. 2. It is remarkable that this number is within the allowed range for the Fayet-Iliopoulos breaking scale as discussed above. For the pattern in Fig. 2 corresponding to case a) we have $g_{GUT} \approx 1.1$, and therefore $M_{GUT} \approx 5.8 \cdot 10^{17}$ GeV.

Of course, we cannot claim to have obtained the Heterotic String unification scale until we have shown that the coupling α_1 joins the other two couplings at M_{GUT} . The analysis becomes more involved now and a detailed account of this issue can be found in ref. [1]. Let us just mention that the fact that the normalization constant, C , of the $U(1)_Y$ hypercharge generator is not fixed in these constructions as in the case of grand unified theories (e.g. for $SU(5)$, $C^2 = 3/5$) is crucial in order to obtain the unification with the other couplings.

3 Phenomenology of this scenario

The main characteristic of the scenario studied in the previous Section, is the presence at low energy of extra matter. In particular, we have obtained that three generations of Higgses and vector-like colour triplets are necessary.

Since more Higgs particles than in the MSSM are present, there will be of course a much richer phenomenology. Note for instance that the presence of six Higgs doublets implies the existence of sixteen physical Higgs bosons, eleven of them are neutral and five charged. On the other hand, it is well known that dangerous flavour-changing neutral currents (FCNCs) may appear when fermions of a given charge receive their mass through couplings with several Higgs doublets. This situation might be present here since we have three generations of supersymmetric Higgses. One approach in order to solve this potential problem is to assume that the extra Higgses are sufficiently

massive. In this case the actual lower bound on Higgs masses depends on the particular texture chosen for the Yukawa matrices, but can be as low as 120–200 GeV.

Concerning the three generations of vector-like colour triplets, say D and \overline{D} , they should acquire masses above the experimental limit $O(200 \text{ GeV})$. This is possible, in principle, through couplings with some of the extra singlets with vanishing hypercharge, say N_i , which are usually left at low energies, even after the Fayet–Iliopoulos breaking. Thus couplings $N_i D \overline{D}$ might be present. From the electroweak symmetry breaking, the fields N_i a VEV might develop.

Before concluding, a few comments about the hypercharges of the extra colour triplets are necessary. For the models studied in refs. [3, 5] they have non-standard fractional electric charge, $\pm 1/15$ and $\pm 1/6$ respectively. In fact, the existence of this kind of matter is a generic property of the massless spectrum of supersymmetric models. This means that they have necessarily colour-neutral fractionally charged states, since the triplets bind with the ordinary quarks. For example, the model with triplets with electric charge $\pm 1/6$ will have mesons and baryons with charges $\pm 1/2$ and $\pm 3/2$. On the other hand, the model studied in ref. [2] has ‘standard’ extra triplets, i.e. with electric charges $\mp 1/3$ and $\pm 2/3$; these will therefore give rise to colour-neutral integrally charged states. For example, a d -like quark D forms states of the type $u\overline{D}$, uuD , etc.

A detailed discussion about the stability of these charged states, how to solve possible conflicts with cosmological bounds, and their production modes can be found in ref. [1].

4 Final comments

We have attacked the problem of the unification of gauge couplings in Heterotic String constructions. We have obtained that α_3 and α_2 cross at the right scale when a certain type of extra matter is present. In this sense three families of supersymmetric Higgses and vector-like colour triplets might be observed in forthcoming experiments. The unification with α_1 is obtained if the model has the appropriate normalization factor of the hypercharge.

Let us recall that although we have been working with explicit orbifold examples, our arguments are quite general and can be used for other schemes where the Standard Model gauge group with three generations of particles is obtained, since extra matter and anomalous $U(1)$ ’s are generically present in compactifications of the Heterotic String.

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